USDA Forest Service
Reseach Paper RM-137

February 1975

WATERSHED MANAGEMENT IN THE ROCKY MOUNTAIN SUBALPINE ZONE:

The Status of Our Knowledge

Rocky Mountain Forest and Range Experiment Station
Forest Service
U.S. Department of Agriculture

Charles F. Leaf

Abstract

Watershed management in the subalpine zone of Wyoming, Colorado, and New Mexico is described. Forest hydrology is briefly discussed, followed by an in-depth discussion and review of (1) field studies of the effects of watershed management practices on snow accumulation, melt, and subsequent runoff; and (2) simulation models designed to predict the hydrologic impacts of timber harvesting and weather modification. Pertinent literature is included, along with unpublished research, observations, and experience. Research needs are highlighted, and guidelines for implementing watershed management principles in land use planning are summarized.

Keywords: Forest management, simulation analysis, snowmelt, subalpine hydrology, watershed management, land use planning.

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Because there is considerable public concern for the ecologic and hydrologic consequences of weather modification, it is important to understand not only how much water yields will be increased, but also how hydrologic systems will be affected. Kahan et al. (1969) were quick to emphasize that systems modeling can play a significant role in analyzing the impacts of increased snow accumulation on water-balance interactions. Accordingly, we have made pre-

[1] *Central headquarters is maintained at Fort Collins, in cooperation with Colorado State University. Leaf is now privately employed in Fort Collins.*

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WATERSHED MANAGEMENT IN THE ROCKY MOUNTAIN SUBALPINE ZONE:

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For many years, much of the research conducted by the Rocky Mountain Forest and Range Experiment Station has been directed to solving problems in watershed management that were generally defined by vegetation zones. Research results have been published as individual articles in many different outlets. As a result, numerous publications are available on different aspects of watershed management. The literature is voluminous and represents a large body of information available for multiple use management. However, this knowledge has not been assimilated for field use. Accordingly, summaries and evaluations of the status of knowledge in the various vegetation zones of the Station territory are being prepared for the practicing hydrologist and land manager.

This report summarizes the status of our knowledge about watershed management in the Rocky Mountain "subalpine zone." It addresses itself to the question: "To what extent are we able to recommend forest management practices to improve water yield, and still maintain acceptable quality, quantity, and timing?" A review of research in the subalpine zone during the past 40 or 50 years is presented, and watershed management guidelines are developed from this comprehensive experimental base.

Simulation models developed by synthesizing the technical information we presently have about separate components of subalpine hydrologic systems are also described. The models have been specifically designed to simulate watershed management practices and their resultant effects on short- and long-term hydrologic system behavior. The potential of these models as planning tools for providing improved information on hydrologic changes resulting from various management strategies is also discussed.

The Rocky Mountain Subalpine Zone

Forest Types

The subalpine zone, as defined in this report, consists of high-elevation forested watersheds where the primary tree species are lodgepole pine, Engelmann spruce-subalpine fir, Douglas-fir, and aspen (respectively, *Pinus contorta*, *Picea engelmannii-Abies lasiocarpa*, *Pseudotsuga menziesii*, and *Populus tremuloides*). Geographically, the area considered lies in Wyoming, Colorado, and New Mexico (fig. 1). Forest surveys for each of these States have recently been published (Choate 1963, 1966; Miller and Choate 1964). A recently published status of knowledge paper by Alexander (1974a) summarizes what we know about the silviculture of the important timber types.

Wyoming's subalpine forests are primarily lodgepole pine, which grow largely on mountain slopes between 7,000 and 10,000 ft in elevation. They lie in the western half of the State on three well-defined mountain formations. The largest forested area occupies the northwestern corner in the vicinity of Yellowstone National Park. The other two include the Bighorn Mountains west of Sheridan, and the Laramie, Medicine Bow, and Park Ranges near the southeastern corner.

Subalpine forests in Colorado range from 8,500 to 11,500 ft above sea level, and straddle the entire length of the Continental Divide from north to south across the State.

Much of the forest occupies high-elevation tablelands. Timber types on tablelands include spruce-fir and aspen, with limited areas of lodgepole pine. The remaining subalpine forest grows on moderate to steep mountain slopes. Principal timber types between 8,500 and 10,500 ft are lodgepole pine, aspen, and Douglas-fir.

Figure 1.—Distribution of spruce-fir and lodgepole pine forests, which comprise the subalpine zone in Wyoming, Colorado, and New Mexico.

Spruce-fir is found between 10,000 and 11,500 ft throughout the Colorado subalpine zone. Lodgepole pine is concentrated in the north-central part of the State, whereas Douglas-fir grows predominantly in the southern half.

New Mexico's subalpine forests are principally Douglas-fir and spruce-fir. Near the upper limits of its 8,000- to 9,500-ft elevational range, Douglas-fir mixes with true firs and spruce. White fir (*Abies concolor*) and aspen are commonly found within the Douglas-fir type. Spruce-fir forests occupy a relatively small area in New Mexico. They are found in the north-central part of the State at elevations between 8,500 to 12,000 ft.

Although aspen forests are common to all three States, the largest stands are found in southwestern Colorado where trees reach 24 inches in diameter at breast height (d.b.h.) and over 100 ft tall.

Alexander (1974b) summarizes current acreages of commercial subalpine forest by State and species on lands subject to management (not reserved in National Parks, Wilderness Areas, and so forth).

Geology and Soils

An excellent summary of the geology and relief of the central and southern Rocky Mountain subalpine zone is presented by Alexander (1974b), who included a number of detailed references on the geologic characteristics of the mountain ranges and plateaus shown in figure 2.

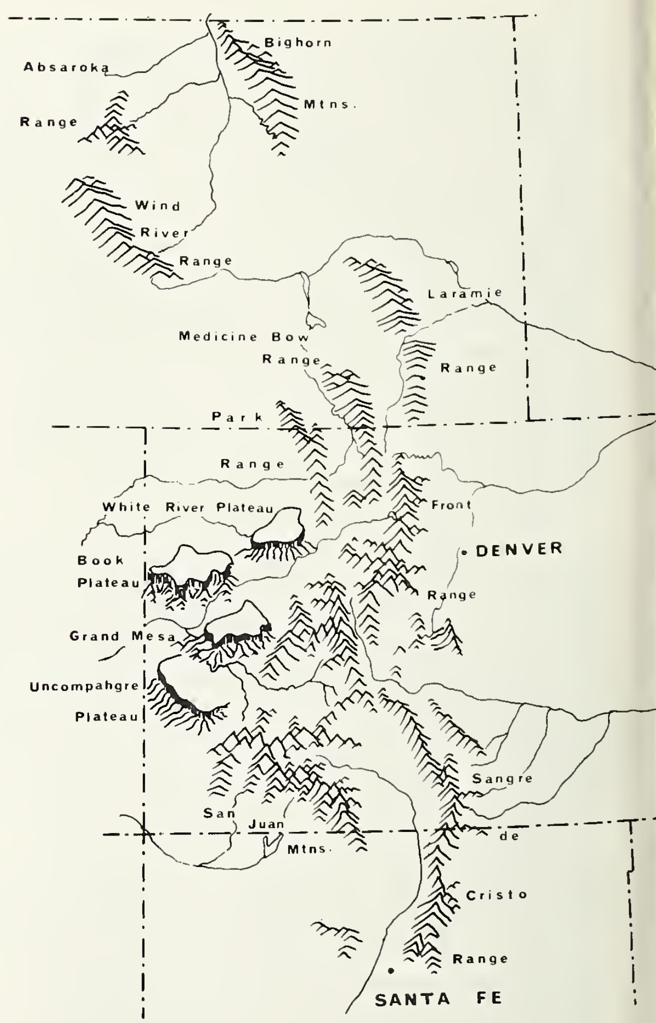


Figure 2.—Important plateaus and mountain ranges of the central and southern Rocky Mountain subalpine zone.

Soils on the subalpine watersheds vary according to the rock from which they originated. In general, the parent material consists of crystalline granite, gneiss, and schist. However, soils derived from sedimentary, basaltic, and volcanic rocks also occupy a large part of the subalpine zone. Alluvial soils occur along most streams. The parent material is generally a mixture of glacial till, glacial outwash, and recent valley fill. Included on most watersheds are bogs originating from seeps and springs which emerge on sideslopes. Soils in these areas are highly organic.

For the most part, subalpine soils are relatively deep, permeable, and capable of storing modest quantities of water from snowmelt. This feature serves to regulate streamflow during the runoff season. Exceptions occur in those areas which have experienced intensive glacial activity, as for example, in most of the Park Range of northwestern Colorado. General descriptions and typical characteristics of subalpine soils are given by Johnson and Cline (1965) and Retzer (1956, 1962).

Water Yield

The subalpine forests of Wyoming, Colorado, and New Mexico form the headwaters of six major river basins (fig. 1):

Wyoming	Colorado	New Mexico
Columbia	Colorado	Rio Grande
Colorado	Missouri	Mississippi
Missouri	Rio Grande	Colorado
Bear	Mississippi	

Water yields from the subalpine zone are of major importance to downstream users. Competition for water is extremely keen, particularly in the Colorado, Rio Grande, and Missouri River basins. Recent decisions by the courts and Federal legislation are good testimonies of the high value that users several hundred miles downstream in Los Angeles, Phoenix, and El Paso place on water which originates in the subalpine forests of Colorado and New Mexico.

The foreseeable increases in water use in areas close to the water source are also of concern to planners. Hardison (1972) has shown that natural streamflows from the subalpine zone are already 80 to 100 percent developed. Thus, future population growth, mining, oil shale, and industrial development will create acute water problems in the long run, unless water supplies are increased through conservation, water management, recycling, and efficient irrigation practices.

Opportunities to use natural flows more efficiently through interbasin diversion and storage still exist. However, new projects are being vigorously opposed by well-organized segments of an environment-conscious society.

Hydrologic Charactistics of Subalpine Forest

Water Balance

Research watersheds have provided us with considerable information about the hydrology of the subalpine zone. Some significant findings from the classic Wagon Wheel Gap experiment (Bates and Henry 1928) were;

- Little, if any, overland flow of water appeared at any season, and the quantity of eroded soil was small.
- Mean annual temperature did not exceed 35°F, and mean annual precipitation was approximately 20 inches.
- Total precipitation was about half snow and half rain. With the exception of south slopes, there was no snowmelt during winter until after early March.
- Of the total precipitation, about one-half is stored in winter snow accumulation and is released during the spring melting period.
- More than 55 percent of the total streamflow occurred from April through June.
- The difference between precipitation and runoff indicated evaporation is a fairly constant 15 inches annually.

Water-balance studies at the Fraser Experimental Forest have also given us insight into the hydrology of spruce-fir and lodgepole pine forests. In developing operational runoff forecasting methods, Garstka et al. (1958) found that water yield is 45 to 55 percent of the annual precipitation. Of this amount, 90 to 95 percent is derived from snowmelt. Typically, winter conditions keep the snowpack well below freezing until late March or April. Peak seasonal snow accumulation averages 15 inches of water equivalent, and during the melt season, the depleting snowpack is augmented by more than 5 additional inches of precipitation. Subsequent rainfall during the summer and early fall averages 8 to 10 inches. Thus, of this 28- to 30-inch input, about 12 to 15 inches becomes streamflow.[2]

[2]Records of temperature and precipitation collected over a 33-year period at the Fraser Experimental Forest have been published by Haeffner (1971). Leaf and Brink (1972a) have also summarized 29 years of streamflow from an experimental watershed in the same area.

Finally, in summarizing a 10-year hydrologic record from the Black Mesa watersheds in western Colorado, Frank[3] found that: (1) more than two-thirds of the 22 inches of precipitation during the average water year fell between October and May; and (2) spring snowmelt accounted for 99 percent of the average annual runoff, which varied from 1.4 to 6.8 inches. Moreover, he also found that summer storms are not severe, with maximum 60-minute rainfall intensities of less than 1 inch per hour, and 5-minute intensities of 4.6 inches per hour. Frank also found that, while summer storm suspended-sediment concentration can be as much as six times that sampled during snowmelt, total suspended sediment for the year is almost nine times that obtained from summer storm runoff "because of the small volume of storm runoff."

The above discussion is a good general account of hydrologic conditions in the subalpine zone, except that melting begins later in the spring in the more northern part of the region and there are small portions that receive more precipitation. For example, in the Park Range in Colorado, at elevations above 10,000 ft, precipitation is between 50 and 65 inches a year with only 20 to 30 percent falling as rain. Water yields average 25 to 45 inches. Other areas of high precipitation and runoff are Flat Tops, San Juans, and the Elk Mountains. Mean annual water balances for typical subalpine watersheds in Colorado and Wyoming are summarized in table 1.

Table 1.--Mean annual water balances (inches) for typical subalpine watersheds in Colorado and Wyoming

Watershed	Seasonal snowpack, water equivalent	Precipitation	Evapotranspiration	Runoff
COLORADO:				
Soda Creek, Routt NF	42.6	55.2	16.7	38.5
Fraser River, Arapaho NF	15.0	30.3	16.9	13.4
Wolf Creek, San Juan NF	26.2	48.0	21.0	27.0
Trinchera Creek, Sangre de Cristo Mountains	9.5	19.6	14.5	5.1
WYOMING:				
South Tongue River, Bighorn NF	15.5	29.6	15.8	13.8

Precipitation

The most accurate and complete snow survey and precipitation measurements have been made at Wagon Wheel Gap and the Fraser Experimental Forest. However, Hoover[4] has pointed out that even these records are suspect, due to the effects of wind on snow accumulation and gage catch. Because snow accumulation and rainfall in subalpine forests are strongly influenced by wind, which interacts with the vegetation and local topography, the existing system of precipitation gages and snow courses in the Rocky Mountain region can at best give only index values of areal precipitation (Meiman 1968, Hoover 1971). A possible exception is a portion of the Park Range near Steamboat Springs, Colorado, where a dense snow course network precisely measures area water equivalent (Washichek and McAndrew 1968).

If a drainage basin is freely accessible to snow measurements, studies have shown that snow input can be measured precisely. Leaf and Kovner (1971, 1972) developed guidelines for estimating total snow storage. From statistical analyses they have shown that, because of the systematic variation of the seasonal snow accumulation, little statistical efficiency can be gained from intensively sampling and extrapolating index snow courses. More precise estimates of areal snow storage can be obtained from reconnaissance snow courses—where one or two samples at most are taken at intervals along a trail which traverses the whole watershed. They have also shown that, on watersheds with uniform forest cover where snow rarely melts during the winter snow accumulation season, the natural snow accumulation can be estimated to within 5 percent of the true mean 50 samples per mi^2 widely spaced over the drainage basin. Similar conclusions can be derived from a study by Swanson (1970), who measured snow accumulation on uniformly vegetated watersheds in Alberta, Canada.

Where severe wind effects produce extremely irregular patterns of snow accumulation in forest margins and exposed parklike openings, Bartos and Rechard (1973) showed that reconnaissance snow courses can precisely

[3]*Frank, Ernest C. Hydrology of Black Mesa watersheds. (Manuscript in preparation at Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo.)*

[4]*Hoover, Marvin D. The influence of forest cover on streamflow in the Central Rocky Mountains. 55 p. (Unpublished Problem Analysis, FS-RM-1602, on file at Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo.)*

estimate areal snow storage, provided that sampling intensities in and near the edges of the large openings are 8 to 10 times greater than well inside the surrounding forest.

As discussed above, snow survey methods can show precisely how the seasonal snowpack is distributed on subalpine watersheds. Once the snowpack begins to melt, however, snow surveys can no longer be used to estimate precipitation input. At this point, and during the summer and fall, rain gages must be used, which in most cases give questionable results due to a host of interrelated factors. Many of these factors have been researched for several hundred years (Larson 1971). Because research using ground-based sensors has largely reaffirmed past results without producing new knowledge, Hoover (1971) suggested that new and different systems which measure precipitation above forest canopies be developed. Laser devices or particle counters, such as those developed by Schmidt and Sommerfeld (1969) and Schmidt (1971), offer promise of better precipitation measurements.

Rhea and Grant (1974) have shown that total snowfall in mountainous area can be largely explained by "systematic consideration of (a) the directionally adjusted topographic slope which potential precipitation-bearing winds must traverse on their last 20 km of approach to a given station, and (b) the number of upstream barriers which the air must pass over." The model should prove to be a highly useful tool for determining seasonal snowfall distribution in unmeasured watersheds and for snow-course network design. Another important benefit from this model is the insight it gives into the physical processes affecting mountain precipitation regimes.

Effects of Timber Harvesting on Snow Distribution

Early studies in the Rocky Mountain region included observations in the natural forest to see how virgin stands affect snow accumulation. Subsequently, plot studies were made of thinnings and patchcuttings to see how these modifications affected the snowpack.

Wilm and Dunford (1948), reporting on plot studies at the Fraser Experimental Forest, gave a comprehensive summary of watershed management concepts and potentials for changing the water cycle in subalpine forests. In their study, twenty 8-acre plots were laid out in mature lodgepole pine in 1938. After careful snowpack measurements, the plots were logged in 1940, ranging from a commercial clearcut of all trees to an uncut virgin area. The residual volume in trees larger than 9.5 inches d.b.h. was in these classes: 0; 2,000; 4,000; or 6,000 bd ft (fbm) per acre. The uncut stands contained 11,900 fbm per acre. After logging, the snowpack was again measured in 1941-43.

Harvest cutting resulted in the accumulation of more snow on the cutover plots. The highest snow accumulation was observed in the clearcut plots. Typical amounts of snow water storage observed immediately after cutting were:

Reserve volume, (fbm/acre)	Inches of water equivalent
11,900 (uncut)	10.3
6,000	11.4
4,000	12.3
2,000	12.4
0 (commercial clearcut)	13.5

The differential snow accumulation observed from this study and from similar studies that followed (Goodell 1952, Goodell and Wilm 1955) was attributed primarily to the elimination of evaporation losses from snow intercepted on the tree crowns which, it was believed, "more than offset increases in evaporation from the snowpack surface caused by removing the shelter of the forest" (Goodell and Wilm 1955).

Based on the plot results, the 714-acre Fool Creek watershed at the Fraser Experimental Forest was partially clearcut in 1954-56 in a pattern of alternate strips varying from one to six tree heights (66 to 396 ft) in width. Fifty percent of the merchantable timber volume was removed from 40 percent of the watershed area (fig. 3). In discussing 3 years of record after the timber harvest, Goodell (1959) suggested that the approximately 25 percent water-yield increase was primarily caused by reduced interception losses associated with the reduction in forest canopy.

This interpretation prevailed until the late 1950's when hydrologists began to seriously question "the conventional emphasis upon interception of snow as an important factor controlling water yield in the Colorado area" (Hoover 1960). In discussing the interception theory, Miller (1961) argued that until the basic processes are carefully studied, the belief that interception results in high evaporation losses from forest canopies is "folklore." Finally, in a reappraisal of the validity of this popular concept, Goodell (1963) summarized existing knowledge and he, too, questioned conclusions previously drawn from interception studies

Figure 3.—Fool Creek watershed, Fraser Experimental Forest. East St. Louis Creek, the 1,984-acre control watershed, is to the right of Fool Creek.

based on differential snow accumulation between uncut forest and adjacent open areas.

More recently, Hoover and Leaf (1967) reported on direct observations of snow accumulation and retention in subalpine forest. These observations indicated that mechanical removal and transport of intercepted snow are more important than vaporization. Conclusions were based on timed-sequence motion pictures of a forested slope during all daylight hours from November 6, 1963, to May 15, 1964. Photographic records during this and subsequent winters proved that snow rests on tree canopies only during periods of cloudy weather, low temperature, and frequent snowfall. Typically, after snowfall ceases, wind-generated vortexes and eddies quickly strip the snow from the trees. In less than a minute, this airborne snow is redeposited at varying distances from where it was intercepted. The sequence in figure 4 shows the obvious importance of redistribution in the subalpine zone.

These results led to the resurvey—first in 1956, and later in 1964, 1968, and 1972—of the cutting plots studied by Wilm and Dunford (1948). Young trees developed rapidly on the clearcut and 2,000-fbm reserve plots (fig. 5). By 1956, the trees averaged 5 ft in height, which placed their canopy above the snow surface. By 1968, their average height exceeded 15 ft.

In spite of vigorous regrowth and increased canopy density on the heavily cutover plots, snow storage amount changed little, if any, in the 28 years since cutting (Hoover and Leaf 1967). These results provided additional evidence that the aerodynamic effect on snow distribution, rather than reduced interception loss, is the major cause of increased snow in openings.

To get still another check, snow survey data from Fool Creek before and after treatment were analyzed to determine the effect of the treatment on a watershed basis (Hoover and Leaf 1967). As observed from the plot studies, comparisons of snowpack in the alternate forest and clearcut strips showed there was more water equivalent in the open strips.

Strip width (chains)	Uncut	Cut
	(inches of water equivalent)	
1	15.4	18.4
2	15.6	17.6
3	17.2	19.2
6	14.0	20.7

To complement the cut-uncut strip comparisons, excellent records of snow storage on Fool Creek and the calibration (East St. Louis Creek) watershed for 11 years before treatment were compared with 7 posttreatment years. Before treatment, total snow storage averaged 14.3 inches on Fool Creek and 11.8 on East St. Louis. For the 7 years observed following treatment, the average water equivalent was 14.4 inches compared with 11.4 inches on the control watershed. These results, shown graphically in figure 6, indicate that total snow storage on Fool Creek was not increased in spite of the obvious differences in snow catch between cut and uncut strips. A similar analysis of winter snow accumulation at Wagon Wheel Gap before and after timber harvesting also showed no change in areal snow storage (Hoover and Leaf 1967). In reviewing this work, Hoover (1971) stated that "If such results are typical of the effect of openings in forest stands, it explains some of the findings of conventional interception studies."

Finally, a recent comparison of snow accumulation and melt in a uniform lodgepole pine stand before and after cutting a small opening

A

B

C

Figure 4.—Significance of wind-caused snow redistribution in the subalpine zone.

A This photograph was taken during moderate snowfall that continued throughout the day of February 4, 1970, at the Fraser Experimental Forest. The storm ceased during the night.

B The most exposed trees were already bare of snow by noon on February 5, 1970. Individual vortexes look like artillery bursts on the mountainsides. Vortexes were moving rapidly eastward (from right to left), and each one was visible for less than 60 seconds.

C By 4:00 p.m. on February 5, 1970, all snow was gone from exposed tree crowns. The white patches are snow in the clearcut blocks on the upper portion of the Fool Creek watershed.

Figure 5.—New growth does not affect total snow storage in this lodgepole pine area of the Fraser Experimental Forest. This 8-acre plot, cut 28 years ago to remove all but 2,000 fbm of trees larger than 9.5 inches d.b.h., still functions as an opening with wind controlled by surrounding old-growth forest.

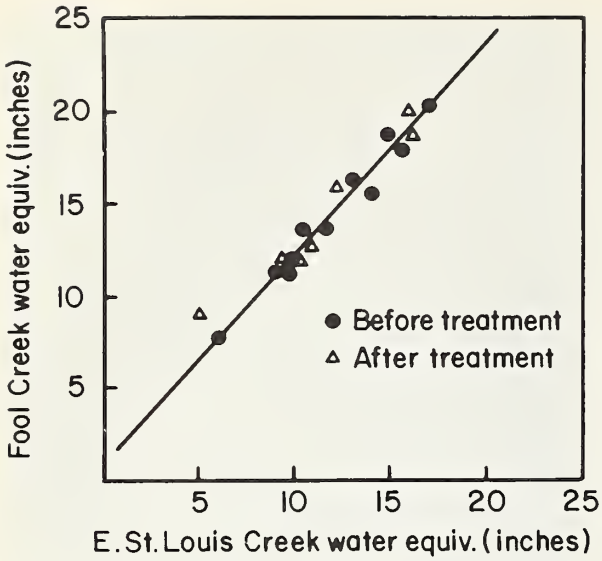


Figure 6.—Comparison of area snow storage before and after strip cutting on Fool Creek watershed.

reconfirmed the significance of redistribution (Gary 1974). Gary found that conspicuous increase in snow accumulation near the center of his opening was largely offset by a decrease in snow below the trees and downwind.

We still need more knowledge of aerodynamic processes and the hydrologic implications of interception and differential snow accumulation. The empirical results summarized above indicate that, for optimum snow accumulation, openings should be protected from wind and should not exceed eight times the height of the surrounding forest (Hoover 1969). Larger openings apparently allow wind eddies to scour the snowpack near the center. A hint of this effect was observed on the 6-chain strips on Fool Creek (fig. 7).

A more complete understanding of interception processes requires more research (Miller 1964, 1966). New work in characterizing the aerodynamic characteristics of subalpine stands (Bergen 1971) will significantly add to what we have already learned from empirical studies.

Snowmelt and Runoff

Snowmelt in relation to subalpine forest cover was studied by Bates and Henry (1928), Wilm and Dunford (1948), Garstka et al. (1958), Gary and Coltharp (1967), Leaf (1971), and Gary (1974). Typically, estimates of peak seasonal water equivalent and ablation during the melt season were derived from weekly measurements of snow courses.

At the Fraser Experimental Forest, Leaf (1971) analyzed snowmelt on two watersheds—Fool Creek (714 acres) with generally east- and west-facing aspects and Deadhorse Creek (667 acres) with north- and south-facing aspects. Leaf observed that, on Fool Creek, snowpack melt rates were generally similar on both aspects at all elevations. In contrast, snowmelt rates on Deadhorse Creek differed considerably between the low-elevation north and south slopes. This agrees with results of Garstka et al. (1958), who reported that, at 9,500 ft on a watershed adjacent to Deadhorse Creek, melt rates on the south slope peaked much earlier than on the opposite north slope. However, Leaf emphasized that the time lag between maximum snowmelt rates on the north and south slopes diminished with increasing elevation. Gary and Coltharp (1967) similarly observed that snowmelt rates were about the same on high-elevation north and south slopes in northern New Mexico.

In the same study, Leaf found that water-yield efficiency was highest on the Fool Creek watershed which had: (1) almost complete snow cover when seasonal snowmelt rates on all major aspects were maximum; (2) a delayed and short snow-cover depletion season; and (3) moderate recharge and evapotranspiration losses.

Water-yield efficiency in Deadhorse watershed, with low-elevation south slopes, was least. In 1969, streamflow from the drainage area on this basin below 9,850 ft was less than 30 percent of that generated from above this elevation. Fourteen years of comparative streamflow

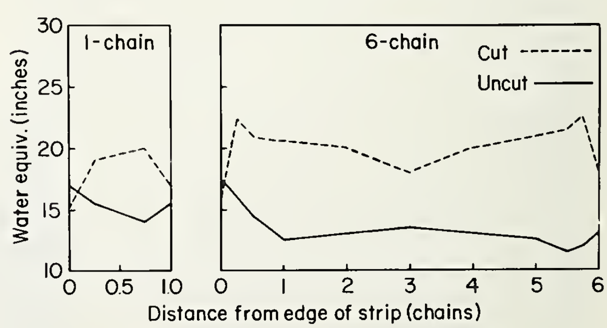


Figure 7.—Comparison of average snow accumulation in one and six tree-height strips on Fool Creek, Fraser Experimental Forest.

data indicated that water yields from the low-elevation subdrainage can vary from near zero in poor runoff years to a maximum during good years of less than 60 percent of the flow generated from the high-elevation subdrainage.

Effects of timber harvesting.—In their experiments in lodgepole pine at the Fraser Experimental Forest, Wilm and Dunford (1948) found that snow melted more rapidly in the heavily cutover stands than in the uncut forest. Moreover, they found that faster melt rates were offset by the higher snow accumulation in the cutover plots so that all the plots became bare of snow at the same time. These results have been confirmed several times in the Rocky Mountain region. The most recent study of this type is discussed by Gary (1974).

At Wagon Wheel Gap in the headwaters of the Rio Grande in Colorado, Bates and Henry (1928) observed accelerated snowmelt rates after clearcutting the aspen-mixed conifer forest from one 200-acre watershed (fig. 8). This effect was apparent in the streamflow hydrograph (fig. 9). Moreover, annual water yields were increased about 22 percent during the 7-year period that records were taken after harvest cutting.

Figure 8.—The Wagon Wheel Gap watersheds some 30 years after treatment. The regenerated forest cover on the clearcut watershed at right is aspen. The control watershed on the left is still vegetated with aspen and mixed conifers.

Timber harvesting on the 714-acre Fool Creek watershed also accelerated snowmelt rates and subsequent streamflow (fig. 10).

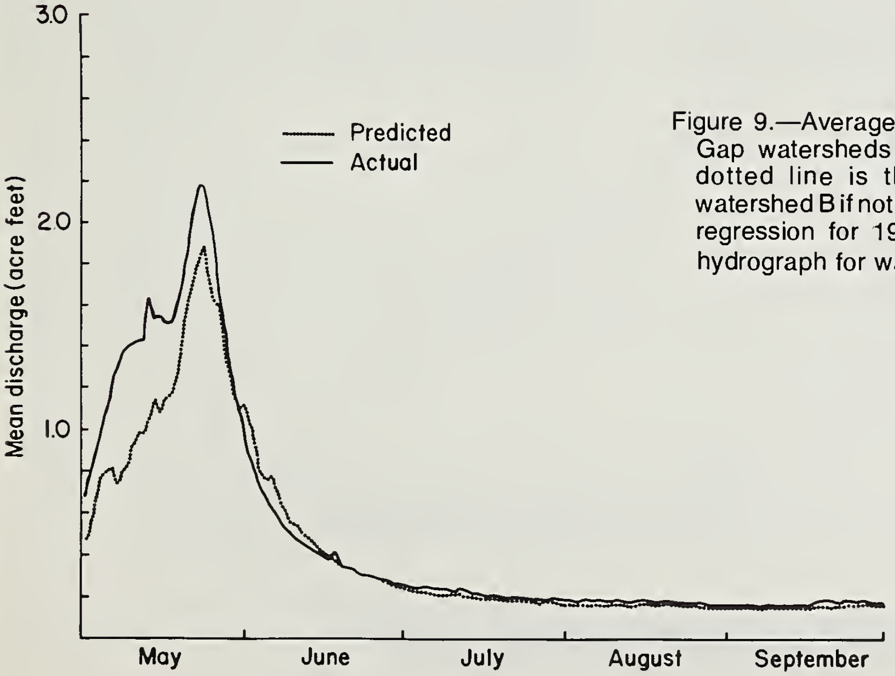


Figure 9.—Average hydrographs for Wagon Wheel Gap watersheds (Bates and Henry 1928). The dotted line is the predicted hydrograph for watershed B if not harvested, based on pre-harvest regression for 1912-19. Solid line is the actual hydrograph for watershed B after timber harvest.

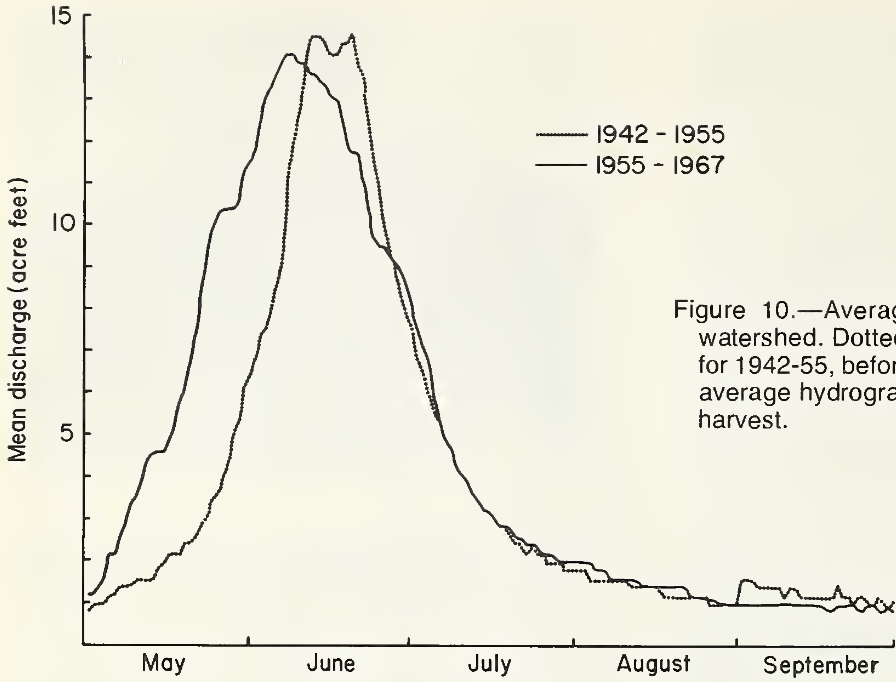


Figure 10.—Average hydrographs for Fool Creek watershed. Dotted line is the average hydrograph for 1942-55, before timber harvest. Solid line is the average hydrograph for 1955-67, following timber harvest.

Water-yield increases have averaged 3.5±0.8 inches at the 95 percent level of confidence since harvest cutting. Statistical analyses indicate that runoff increases may have begun to taper off somewhat in recent years (fig. 11).

Another significant result from this watershed study was that peak flows apparently were not significantly affected. Leaf (1970) pointed out that, for the pretreatment period from 1943 to 1955, annual peak daily flows averaged 9.7 cubic ft per second (ft^3/s), compared with an average 9.5 ft^3/s for the 1956 to 1969 postharvest periods.Finally, hydrograph comparisons indicate that recession flows were not diminished, even though timber harvesting caused higher snowmelt rates in early spring and more efficient water yield. Water yields before and after harvest cutting from Fool Creek and the East St. Louis Creek control watershed are compared in figure 12.

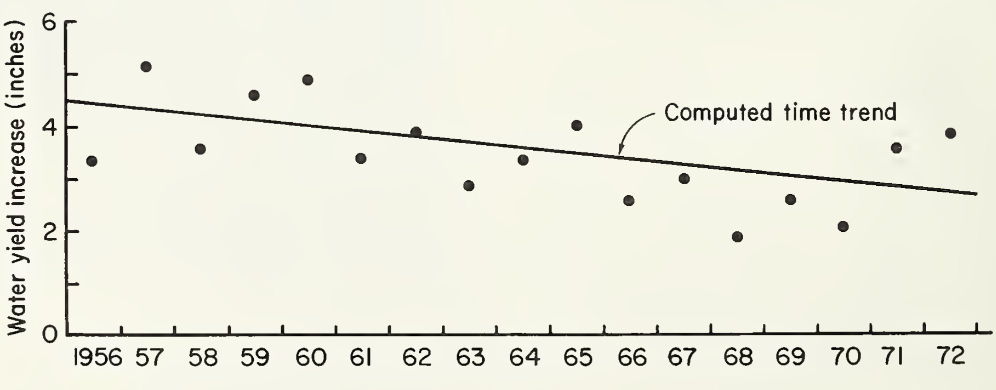


Figure 11.—Summary of increased water yields subsequent to strip cutting on Fool Creek.

Yet another illustration of increased water yields was given by Love (1955, 1960), who studied a larger 762-mi^2 watershed which drains the White River above Meeker, Colorado. In this instance, beetles killed 26 to 80 percent of the spruce-fir forest on a 226-mi^2 area. Love observed that average annual flow in the White River was increased by 25 percent. He attributed the increase to the same effects that increased water yields from Fool Creek, which included reduced interception and evapotranspiration.

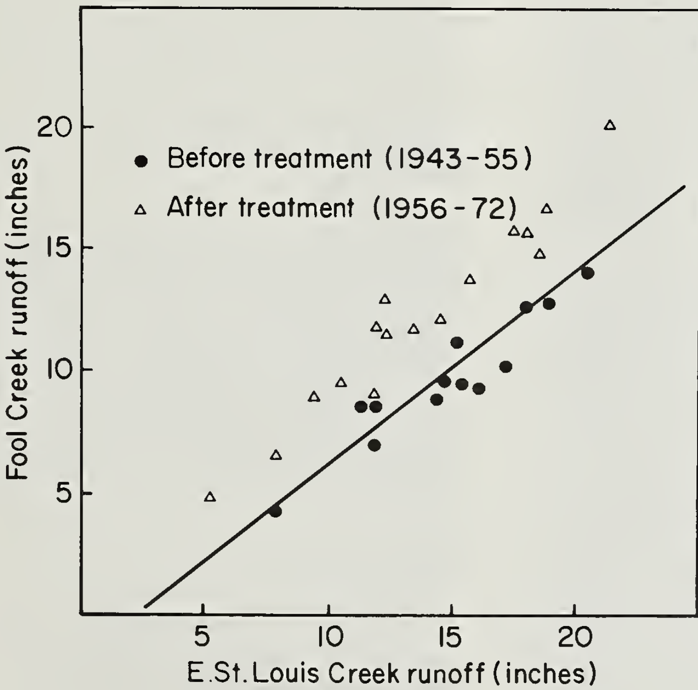
Effects of grazing.—In much of the subalpine zone, watersheds are not completely forested, but are covered with stands of spruce and aspen intermingled with extensive grassland parks. Such areas are not only important for water yield, but also for wildlife habitat, forage, and livestock production. Thus, in addition to forest hydrology, range hydrology is also important in determining the total water balance of these lands.

A considerable amount of research has been done in rangeland watershed management along the Front Range of Colorado and in central Arizona (Gary 1975). These studies covered a variety of grasses, soils, elevations, and climates, in rather low water-yielding zones. In Colorado, it was found that good plant cover on coarse and porous soils minimizes surface runoff and erosion. However, Gary(1975) has concluded that, while these studies have shown that good range management practices and revegetation of depleted land with trees, shrubs, and grass will improve watershed conditions, such measures cannot offer complete protection against intense runoff and normal geologic processes which are characteristic of the Front Range.

It should be noted that much of the early concern for protection of western Colorado mountain rangelands originated from infiltrometer studies in which artificial rainfall was applied to prewetted plots at a rate of 5 inches per hour for a 50-minute period (Turner and Dortignac 1954). These rates were approximately five times the maximum observed rainfall intensities on Black Mesa.

Frank[5] demonstrated that there was not a significant change in runoff and sediment under various intensities of cattle grazing at

[5]*Frank, Ernest C. Hydrology of Black Mesa watersheds. (Manuscript in preparation at Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo.)*



April - Sept.
Runoff Increase
Since Harvest

Year	Inches
1956	3.3
1957	5.2
1958	3.7
1959	4.6
1960	5.4
1961	3.4
1962	3.9
1963	2.9
1964	3.5
1965	4.0
1966	2.6
1967	3.1
1968	1.9
1969	2.5
1970	2.1
1971	3.6
1972	3.9
Mean	3.5 $\pm$0.8*

*95 Percent level of confidence

Figure 12.—Comparison of seasonal runoff before and after strip cutting on Fool Creek watershed.

Black Mesa since: (1) virtually all of the runoff and sediment yield was produced during the snowmelt runoff season; and (2) 60-minute rainfall intensities seldom exceed 1 inch per hour. Moreover, grazing intensities on the watersheds were set up to obtain 25 to 60 percent utilization of only one range species (Idaho fescue, *Festuca idahoensis*). Therefore, it was difficult to obtain a strong indication of differences in runoff and sediment resulting from changes in ground cover. Frank's results were based on an analysis of watersheds which required rather large differences in water yield (0.6 to 2.2 inches after 10 years) before any effect could be detected.

Given the above, it would be premature to conclude that grazing does not affect water yields. On the contrary, Schuster (1964) reported that heavy grazing can decrease the amount of root material. It is reasonable to expect that any detrimental effects on root systems would reduce consumptive use and thereby increase water yields somewhat. Our knowledge as to whether or not this increase is significant requires further research.

Hydrologic Systems Analysis: Subalpine Hydrologic Simulation Model

As discussed above, a considerable body of knowledge accumulated during the past 50 years has conclusively shown that subalpine forests indeed exert a significant effect on water yields. Hoover[6] has pointed out that, in lodgepole pine and spruce-fir forests, where water is a primary resource, "... sufficient practical information exists to guide the first steps in applying management for increased water yield."

In spite of this position, land managers are apparently reluctant to specifically include watershed management principles in their multiple use planning—perhaps for three technical reasons: First of all, as will be discussed later, there is still a deficiency in scientific knowledge of specific processes; secondly, there is a lack of "management tools" to translate research results into management decisions; and finally, nature has so blessed much of the Rocky Mountain region with excellent water supplies during the past 20 years, that society is complacent as to the limitations of this vital resource. Nevertheless, planners have already concluded that the "thorniest problem facing energy development in the West is water" (Engineering News Record 1974). Unless alternative water sources are developed, and the present rate of use curtailed to accommodate growth and environmental needs, severe water shortages are sure to occur in the future.

The recent clearcutting controversy (Wyoming Study Team 1971) has made it emphatically clear that the public wants a high caliber of natural resource management. Accordingly, we must apply everything we have learned about the subalpine ecosystem —including what we have learned from watershed management research—in reaching management decisions.

Although we still have an imperfect scientific understanding of how specific hydrologic processes operate, we cannot afford to wait for new information. Rather, we must begin to use what we presently know. The systems approach, where a dynamic simulation model is built from available knowledge about separate components, is one way to incorporate research results into operational resource management. This is a technically sound procedure that has had a history of success (Forrester 1961).

Leaf and Brink (1973a, 1973b) have developed a comprehensive hydrologic model which simulates the water balance in several hydrologic subunits within a subalpine watershed on a continuous year-round basis, and compiles the results from up to 25 subunits into a "composite overview" of the entire drainage. The model has been specifically designed to simulate watershed management practices and their resultant effects on hydrologic system behavior.

The discussion which follows is intended to give a general idea of the scope of the model. Detailed flow chart descriptions and more complete hydrologic theory are presented by Leaf and Brink (1973a, 1973b), who developed the model from more than 25 years of field data collected from subalpine watersheds in the Fraser Experimental Forest. The model has also been calibrated for several representative areas throughout the Rocky Mountain region. A general flow chart of the system is shown in figure 13.

Snowmelt

Previous work in subalpine forests has shown that radiation is the major source of energy for snowmelt (Bergen and Swanson 1964). Accordingly, shortwave and longwave radiation represent the energy components available for snowmelt. Shortwave radiation to the snow or ground surface beneath the forest

[6] *Hoover, Marvin D. The influence of forest cover on streamflow in the Central Rocky Mountains. 55 p. (Unpublished Problem Analysis, FS-RM-1602, on file at Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo.)*

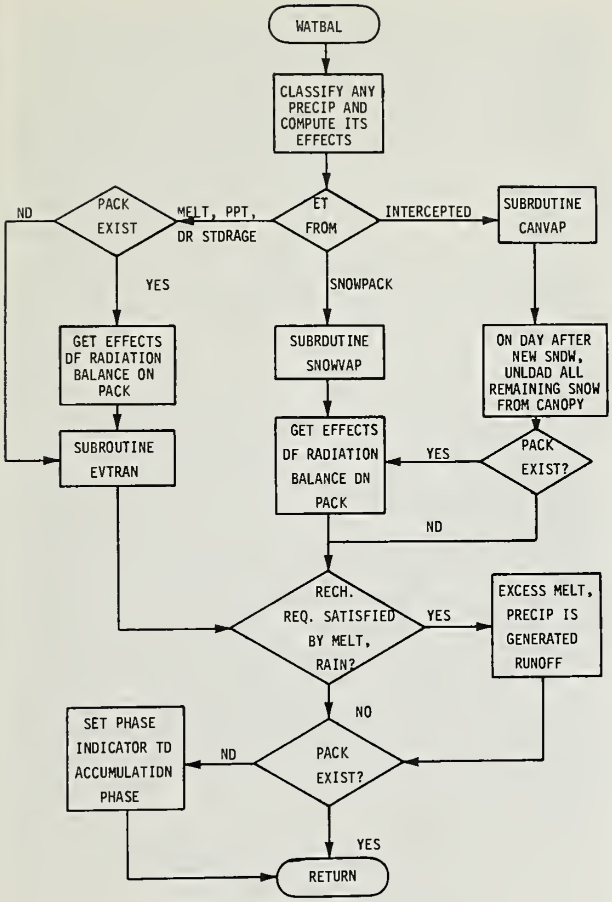


Figure 13.—Flow chart of dynamic model which simulates subalpine hydrology.

canopy is controlled by a transmissivity coefficient which varies according to forest cover characteristics. The incident shortwave radiation as measured on a horizontal surface is adjusted according to the slope and aspect of each hydrologic subunit. Longwave radiation is computed by the Stefan-Boltzmann equation.

Snowpack reflectivity varies according to precipitation form, air temperature, and the energy balance. During the winter months, temperatures within the snow cover are simulated using unsteady heat flow theory. The snowpack will yield melt water only when it has become isothermal at 0°C, and its free water-holding capacity is reached.

Interception and Evapotranspiration

We do not yet have a complete understanding of evapotranspiration on an areal basis. What we do know is summarized below:

1. Little or no evaporation from snow was observed by Wilm and Dunford (1948), who also found that nearly all evaporation took place after melting began. More recently, Hutchison (1966) reported that rapid evaporation occurred from wet soil around melting snow with possible condensation on snow surfaces. Model studies of an unripened snowpack by Bergen (1963) indicated that substantial amounts of water vapor were lost from the deepest layers of the pack, and that free convection took place within the pack during winter. Bergen also observed that evaporation from the snow surface can be relatively high during clear weather in late spring.
2. In comparing soil-moisture regimes after snowmelt in aspen and spruce, Brown and Thompson (1965) showed that both spruce and aspen remove soil moisture to 8 ft. They also observed that the rate of water use was related to available water, as did Swanson (1967, 1969). Swanson also obtained information on the diurnal and seasonal course of transpiration in subalpine forests. He found that transpiration can occur early in the melt season when there is still considerable snow cover. Using heat-pulse methods, he also observed distinct velocity profiles in the conducting tissue of tree stems. More recently, Swanson (1972) showed that heat pulse velocity (HPV) is a function of both transpiration and water stored in tree parts. When internal plant water stresses were low, HPV directly indicated transpiration rate, whereas HPV was poorly related with transpiration at higher stresses.
3. Dahms (1971), reporting on a levels-of-growing study in lodgepole pine in Oregon, observed that soil-moisture withdrawal was reduced only at the lowest stand densities. By comparing periodic annual soil-moisture withdrawal for 10 years in five levels of growing stock (1 = lowest, 5 = highest), Dahms observed a sharp decrease in soil-moisture withdrawal by the low-density stand (level 1) and no significant difference in soil-water use between levels 2 through 5. He also observed that "soil moisture was withdrawn largely from the upper part of the soil during the early part of the season. However, as the summer advanced and most of the water in the upper portion of the soil had been used, soil moisture from the deeper layers was required for transpiration demands." Soil moisture was withdrawn to a depth of more than 5 ft in August and September.
4. Finally, soil-water measurements by Dietrich and Meiman (1974) in lodgepole pine in

north-central Colorado indicate that fall soil-moisture deficits in the top 2 meters were substantially less in small patchcut openings than in the surrounding forest.

Using this background information and results from the differential snow accumulation studies discussed earlier, a "potential" evapotranspiration function was developed for the model based on the empirical Hamon equation (Hamon 1961), which requires latitude, converted to saturation vapor density. The coefficient, C, in Hamon's equation was adjusted upward to obtain an expression for potential evapotranspiration under "unlimited" solar input, assumed here as potential radiation. The evapotranspiration computed by this expression is reduced in proportion to the radiation actually received each day. The adjusted evapotranspiration is then redefined according to its source, which can include: evaporation from snow intercepted by the forest canopy; evaporation from the snowpack surface; and evapotranspiration during the growing season (presumed to begin when areal snowpack water equivalent is reduced to 5 inches).

In developing the intercepted portion of the model, it was assumed that:

- The amount of snow intercepted varies according to forest cover type and density;
- The intercepted snow rests on the canopy for only 1 day following the day of the snow event due to turbulent winds which remove snow from the crowns; and
- The residual intercepted snow which is not vaporized after that period of time is added to the snowpack.

If the source is evapotranspiration, further adjustments are made to account for available soil water in open or forested areas, and the reflectivity of open or forested areas.

Input to the watershed system is derived from snowmelt and rainfall. Once evapotranspiration requirements have been satisfied, any remaining input is used to satisfy soil mantle recharge requirements. When "field capacity" is reached, the residual input becomes water available for streamflow (generated runoff).

Hydrologic Subdivisions

A given subalpine watershed system can be subdivided into as many as 25 hydrologic subunits. Subunits can vary according to elevation, slope, aspect, and forest cover. The model is designed to output results from individual subdivisions or compute area-weighted averages to get an overall response for the entire basin. In this way, both time and spatial variations are realistically accounted for. Table 2 summarizes the environmental characteristics of 10 subunits within a 667-acre subalpine watershed at the Fraser Experimental Forest. Individual subunits average 10 percent of the total area.

Systems Analysis of Watershed Management Practices

Forrester (1961) has emphasized that the major worth of dynamic models lies in their ability to precisely predict system response

Table 2.--Environmental characteristics of Deadhorse Creek watershed, Fraser Experimental Forest (Elevation: 9,600-11,600 ft, m.s.l. General aspect: ENE Latitude: 40°N)

Units and subunits	Percent of total area	Elevation range	Slope	Aspect	Vegetation type	Cover density	Transmissivity
		Ft	*Percent*			*Percent*	
LOWER BASIN:	(37)						
Lower South	12.6	9,600-10,400	30	SSE	Lodgepole pine	40	35
Middle North	6.1	9,600-10,200	45	NNE	Lodgepole pine	40	35
Lower North	6.0	9,600-10,200	40	N	Spruce-fir	65	25
Lower East	12.4	9,600-10,600	40	SE	Lodgepole pine	45	30
UPPER BASIN:	(63)						
Upper North, Subalpine	10.3	9,800-10,600	35	NE	Spruce-fir	55	25
Upper North, Alpine	7.8	10,600-11,600	35	NE	Spruce-fir	0	100
Upper East	17.9	9,800-11,200	30	ESE	Lodgepole pine	35	40
Upper South, Forested	12.0	10,200-11,000	30	SSE	Lodgepole pine	30	40
Upper South, Teardrop	1.6	10,800-11,000	30	SSE	Lodgepole pine	0	100
Middle South	13.1	9,800-10,600	30	SSE	Lodgepole pine	25	45

from changes in one or several system components. We have used this approach to study the effects of proposed watershed management practices on undisturbed watersheds, using our best information from field studies and the model described above.

Patchcutting

Snowmelt.—In simulating a proposed cutting practice on Deadhorse Creek at Fraser, the snowmelt portion of the model has produced results similar to those observed from field studies. Leaf and Brink (1972b) assumed that 40 percent of the watershed area was uniformly patchcut in openings five tree heights in diameter. As discussed previously, research has shown that more snow accumulates in openings, but total snow storage is apparently not changed significantly following harvest cutting. Accordingly, the snowpack was increased 30 percent in the openings and decreased 20 percent in the uncut forest to simulate the timber harvest.

Apart from redistribution of the snowpack, only the forest cover density variable was adjusted in the model to represent the timber harvest system. This in turn affected the energy balance and associated hydrologic components. Leaf and Brink (1972b) assumed that "the radiation balance in the center of the clearings could be represented by the balance computed for large open areas. Thus, the energy exchanges which produce intensive melt near sunlit margins compensate for reduced snowmelt near shaded margins."

Manipulating the snowpack and forest cover parameters in the calibrated model indicates that cutting small openings in mature subalpine forest results in increased snowmelt early in the melt season and diminished snowmelt later. Although patchcutting affected the timing of snowmelt, it apparently did not significantly change the duration of the snowmelt season. Under comparable conditions, snowmelt began a few days earlier in small openings on all aspects, but in both the natural forest and cutover areas, the last snow melted at about the same time. Because melt rates in openings were higher early in the snowmelt season, results indicated that peak streamflow would not be increased appreciably, if at all, under the assumed timber harvesting alternative. Figure 14 summarizes the predicted average change in snowmelt input resulting from this practice for the 1964-71 period of record at the high-elevation north-slope and the low-elevation south-slope locations.

Water yield.—In addition to redistributing the snowpack and accelerating snowmelt runoff, the assumed timber harvesting practice

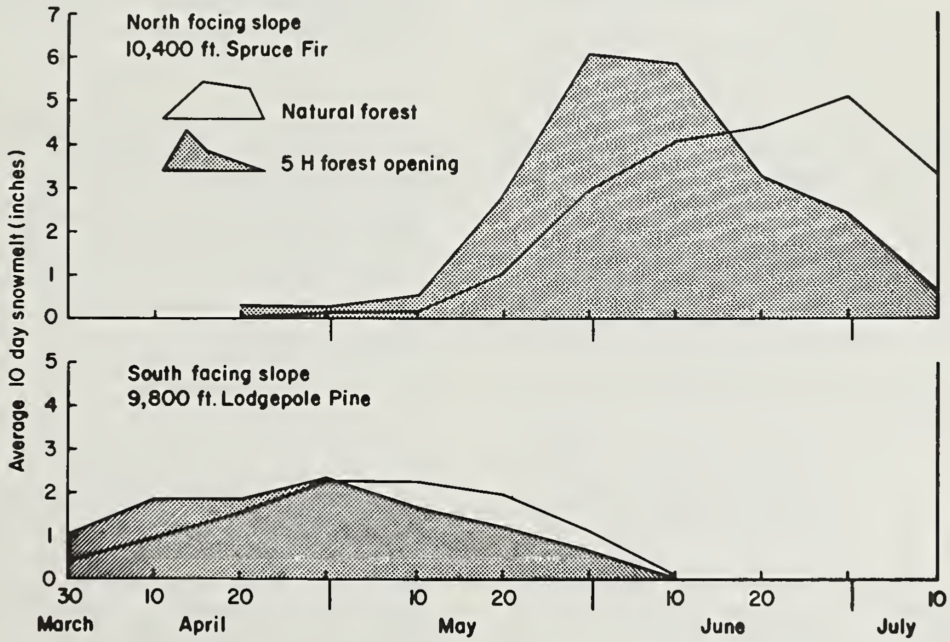


Figure 14.—Comparisons of simulated average snowmelt rates in five-tree-height openings with natural old-growth forest, 1964-71.

also affected evapotranspiration in several respects. During the snow accumulation and melt seasons, evaporation of intercepted snow was decreased in proportion to the amount of vegetation removed. However, evaporation from the snowpack in the small openings was higher, resulting in greater losses than from snow in uncut forest. Finally, evapotranspiration during the growing season was also reduced in proportion to the amount of forest cover removed. This reduced evapotranspiration resulted in lower recharge requirements over the basin. It should be emphasized that our simulation analyses failed to confirm the hypothesis that increased streamflow results from decreased interception loss. Higher evaporation losses from exposed snow surfaces in areas formerly under dense forest cover almost compensate for reduced interception losses. Thus, net input is increased less than 0.5 inch. This compares with more than 2 inches of additional streamflow resulting from the timber harvest. The combined action of redistribution and reduced evapotranspiration is the primary cause for increased water yields from subalpine forests. As Hoover and Leaf (1967) have pointed out, concentrating snowpack in openings where recharge requirements are least results in more efficient delivery of snowmelt runoff from the system.

Simulated data for 1947-71 water years (table 3) were averaged; results for this period are plotted in figure 15. (Note that, with the exception of snowpack water equivalent, all hydrologic components are plotted as 6-day means.)

The simulated average runoff increase for the 1947-71 record period, 2.1 inches, resulted from a 2.1-inch decrease in evapotranspiration losses, with no change in storage. Average recharge requirements in the fall were decreased by 1 inch. As discussed above, snowmelt timing and resultant streamflow were also changed. Figure 15(c) shows that generated runoff was increased during April, May, and the first part of June, and diminished somewhat thereafter. Because the generated flows are routed through natural storage in the watershed to produce the hydrograph, it is reasonable to expect that the recession limb of the seasonal hydrograph would not be significantly changed due to treatment. However, stream discharges would be higher on the rising limb, as observed from the Fool Creek and Wagon Wheel Gap watershed experiments (see figs. 9 and 10).

It is worth noting here that the assumption regarding the onset of transpiration, when the snowpack is melted down to 5 inches of water equivalent, accounts for the difference between the change in growing-season evapotranspiration and the change in fall recharge requirement (-1.7 inches versus -1.0 inch in table 3).

The results above refer to hydrologic changes for an entire watershed. Because hydrologic regimes of subunits within even small

Table 3.--Simulated hydrologic changes (water balance, in inches) resulting from patchcut timber harvesting, Fraser Experimental Forest (Average of 1947-71 water years)

Component	SUBALPINE FOREST (1,687-acre composite of 3 experimental watersheds)			LODGEPOLE PINE FOREST (Low elevation, south slope)			SPRUCE-FIR FOREST (High elevation, north slope)		
	Natural	Treated[1]	Change	Natural	Treated	Change	Natural	Treated	Change
	Inches								
Precipitation	30.6	30.6	0	23.5	23.5	0	30.2	30.2	0
Evapotranspiration:									
Canopy	2.0	1.0	-1.0	1.7	.8	-.9	2.2	1.1	-1.1
Snow surface	2.9	3.5	+.6	1.2	1.5	+.3	2.1	2.5	+.5
Growing season	11.6	9.9	-1.7	14.8	12.9	-1.9	9.9	8.5	-1.4
Total	16.5	14.4	-2.1	17.7	15.2	-2.5	14.2	12.1	-2.1
Recharge requirements:									
Beginning (Oct. 1)	3.4	2.4	-1.0	4.3	2.9	-1.4	3.1	2.3	-.8
End (Sept. 30)	3.4	2.4	-1.0	4.3	2.9	-1.4	3.1	2.3	-.8
Water yield	14.1	16.2	+2.1	5.7	8.2	+2.5	15.7	17.8	+2.1

[1]Figures in this column represent weighted values for both forested and nonforested areas.

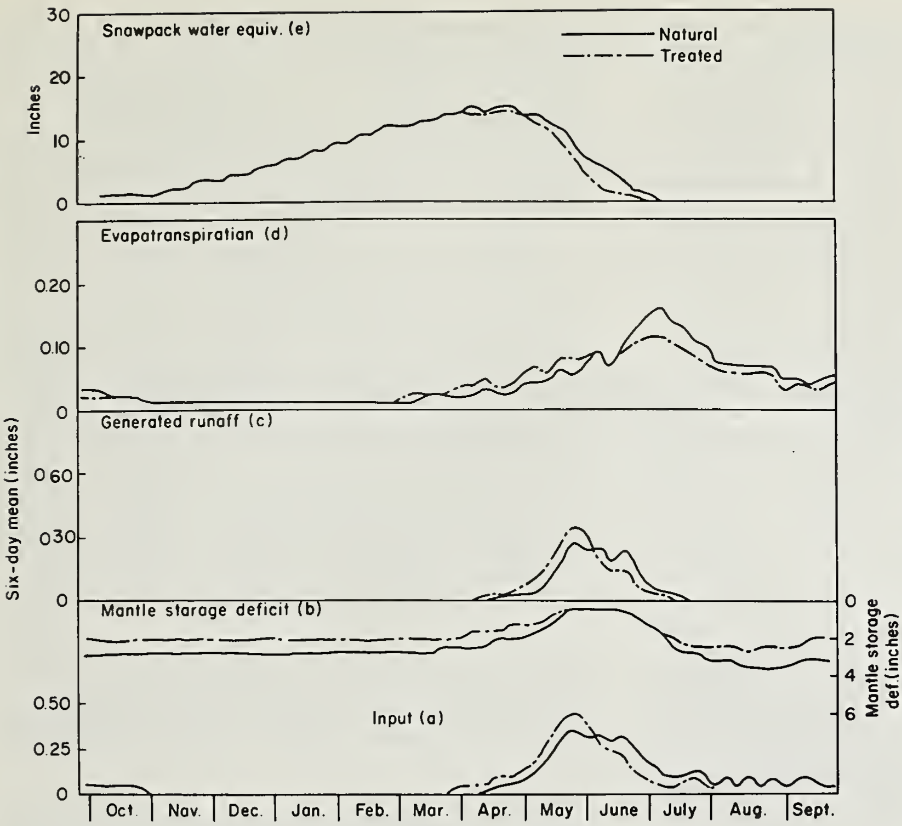


Figure 15.—Simulated average water balance for the 1947-71 water years, showing changes resulting from cutting small openings in old-growth subalpine forest (1,687-acre composite of three experimental watersheds).

forested watersheds can vary by several orders of magnitude (Leaf 1971), similar analyses were made on each subunit. Results from the low-elevation south slopes (9,000 ft) and high-elevation north slopes (10,200 ft) are also summarized in table 3.

First, it is significant that, in their natural states, the low south slopes are less than half as efficient as high north slopes in producing streamflow (24 percent versus 52 percent). At first thought, it would appear that potentials for water-yield improvement are highest in the spruce-fir forests where precipitation is greater (30.2 inches on north-slope spruce-fir versus 23.5 inches on south-slope lodgepole pine) and consumptive use is least (9.9 inches versus 14.8 inches). Apparently this is not the case, however. As seen in table 3, the changes produced in each hydrologic component are apparently the same order of magnitude on all aspects when timber is cut in small patches. Thus, the increment of increased water yield is approximately uniform over the entire basin. This result has important management implications. It implies that there is no reason to favor those areas with the highest natural water yields if the objective is to maximize streamflow from medium- to high-density stands of old-growth pine and spruce-fir.

Selection Cutting

Table 4 summarizes predicted hydrologic changes when the canopy cover density is uniformly reduced 50 percent on the entire watershed. (It was assumed that this option corresponds to removal of at least 40 percent of the timber volume.) A comparison of tables 3 and 4 shows that patchcutting apparently increases water yields considerably more than does individual-tree selection cutting—2.1 inches against 0.4 inch. In the selection-cutting option, evapotranspiration during the growing season is decreased only 0.4 inch compared to 1.7 inches for patchcutting. Moreover, fall recharge requirements are decreased by only 0.3 inch compared to 1.0 inch. Overall, the effect on snowmelt timing in the latter case is not large. Snowmelt can be accelerated or delayed when the forest canopy is reduced, depending upon aspect; however, in no case is the change in timing as large as with patchcutting.

Predicted hydrologic changes resulting from a 50 percent forest cover density reduction on north-and south-slope subunits are also summarized in table 4. In contrast to patchcutting, the selection-cut option apparently can have both postive and negative water yield effects, depending on aspect and vegetation type.

Table 4.--Simulated hydrologic changes (water balance, in inches) resulting from selection cutting, Fraser Experimental Forest (Average of 1947-71 water years)

Component	SUBALPINE FOREST (1,687-acre composite of 3 experimental watersheds)			LODGEPOLE PINE FOREST (Low elevation, south slope)			SPRUCE-FIR FOREST (High elevation, north slope)		
	Natural	Treated	Change	Natural	Treated	Change	Natural	Treated	Change
	Inches								
Precipitation	30.6	30.6	0	28.6	28.6	0	32.3	32.3	0
Evapotranspiration:									
Canopy	2.0	1.1	-.3	2.1	1.1	-1.0	2.2	1.7	-.5
Snow surface	2.9	3.8	+.9	2.1	2.8	+.7	2.4	3.7	+1.3
Growing season	11.6	11.2	-.4	14.5	14.0	-.5	9.5	9.2	-.3
Total	16.5	16.1	-.4	18.8	18.0	-.8	14.2	14.6	+.5
Recharge requirements:									
Beginning (Oct. 1)	3.4	3.1	-.3	4.1	3.9	-.2	2.8	2.4	-.4
End (Sept. 30)	3.4	3.1	-.3	4.1	3.9	-.2	2.8	2.4	-.4
Water yield	14.1	14.5	+.4	9.8	10.6	+.8	18.1	17.6	-.5

On south slopes in lodgepole pine, water yields are increased almost an inch, whereas on north slopes in spruce-fir, yields are apparently decreased as much as 0.5 inch. This decrease is primarily due to higher snowpack evaporation losses. At the higher elevations on north aspects, the longer melt season results in a 1.3-inch higher evaporation loss from snow surface compared to an 0.7-inch increase on south slopes. Reduced interception losses apparently compensate for less than half of the increased snow evaporation on north slopes, whereas on south slopes, reduced interception and increased snow evaporation are the same order of magnitude.

The simulated basinwide effects of cover density reduction are summarized according to aspect and forest cover type in table 5. It is significant that uniform canopy reduction results in less water yield in all of the response units in spruce-fir forest, whereas water yields are increased somewhat in all but two of the subunits in lodgepole pine.

Reliability of Results from Simulation Model

Most of the research in subalpine watershed management has been concerned with natural conditions or with the effects of complete removal of the forest cover. Very few studies have been made to determine the hydrologic impacts of individual-tree selection cutting. Accordingly, results obtained from the patchcutting options in the model should be considered as the most reliable. The energy and water balances of partially opened stands must be studied further before results from the

Table 5.--Simulated water yield changes resulting from a 50 percent forest cover density reduction according to aspect and forest type

Subunit and aspect	Forest cover type	Percent of area	Water-yield change
			Inches
[1]1 --SSE	Lodgepole pine	6.5	+0.8
2 --NNE	Lodgepole pine	2.4	+.3
3 --N	Spruce-fir	2.4	-.9
4 --SE	Lodgepole pine	6.9	+.5
[1]5 --NE	Spruce-fir	5.8	-.5
6 --ESE	Lodgepole pine	10.5	+.8
7 --SSE	Lodgepole pine	7.0	+1.1
8 --SSE	Lodgepole pine	9.2	+1.6
9 --NNW	Lodgepole pine	7.6	+1.0
10 --NW	Spruce-fir	7.6	-.4
11 --NNW	Spruce-fir	4.2	-.1
12 --N	Spruce-fir	4.2	-.1
13 --NNE	Lodgepole pine	12.6	-.4
14 --NE	Lodgepole pine	2.1	+.6
15 --NE	Lodgepole pine	2.1	-.2
16 --Natural open areas		8.9	0
Total for 1,687-acre composite[2]		100.0	+.4

[1]Hydrologic changes in subunits 1 and 5 are summarized in table 4.

[2]See table 4.

selection-cut options in the model can be verified. Nevertheless, selection cutting in the spruce-fir on northerly aspects may not significantly increase water yields at best; water yields may actually be decreased. In the lodgepole pine type, the model predicts that water yields can be increased provided that selection cuts are made on southerly aspects and at low elevations where the snowmelt season is short and begins relatively early in the spring. On a watershed basis, increased water yields from selectively cutting about 40 percent of the timber volume are far less than the increases generated when the same volume is removed by patchcutting. Rich (1965) observed similar results when he studied the effects of selection cutting and clearcutting in Arizona mixed conifer watersheds. Rich found that a commercial timber harvest on an individual-tree selection basis did not significantly increase water yields, whereas a moist-site clearcut increased streamflow by 46 percent.

Silviculture

It should be emphasized that the timber harvesting measures recommended for water-yield improvement are silviculturally sound and compatible with the guidelines recently developed by Alexander (1972, 1973, 1974b) for partial cutting in old-growth lodgepole pine and spruce-fir. This type of management would preserve the natural landscape by maintaining continuous forest cover in areas of high recreational value. In developing the guidelines, Alexander carefully considered: (1) stand conditions, (2) windfall risk, and (3) insects and diseases. Specific management alternatives are also recommended for integrating water and timber production which would include cutting options proposed by Alexander in combination with small cleared openings to favor increased water yields.

Weather Modification

Weather modification technology in the Rocky Mountain subalpine zone has evolved to the point where pilot projects are being started to increase water yields. One of the largest of these is the "Colorado River Basin Pilot Project," sponsored by the Division of Atmospheric Water Resources, Bureau of Reclamation.

Effects of cloud seeding have been evaluated in several ways. The most widely used approach has been statistical detection of snow accumulation and runoff increases, and much has been done in recent years to improve the power of the more classical statistical tests (Morel-Seytoux 1972).

Because there is considerable public concern for the ecologic and hydrologic consequences of weather modification, it is important to understand not only how much water yields will be increased, but also how hydrologic systems will be affected. Kahan et al. (1969) were quick to emphasize that systems modeling can play a creased snow accumulation on water-balance interactions. Accordingly, we have made preliminary studies with the Subalpine Water Balance Model to quantify the hydrologic effects of successful weather modification. These studies were based on an assumed 15 percent increase in winter snowfall between November 30 and March 31. In this case, the increased snow accumulation: (1) had little effect on evapotranspiration and soil water storage; and (2) did not extend the duration of the melt season more than 3 to 5 days. Approximately 90 percent of the increased snowpack produced streamflow. Typical results from the 15-percent-increase analyses are summarized in table 6 and figure 16. An average 2.4 inches of increased water equivalent for 1947-71 on a 667-acre subalpine watershed in central Colorado produced an average 2.2 inches of additional water yield, with a 0.2-inch increase in evapotranspiration and a negligible effect on soil-water storage. Because water-yield benefits result from the last snowmelt at a given location, the bulk of the increased runoff is released during and just after peak streamflow. This would have a tendency to broaden the snowmelt hydrograph and possibly increase peak flows (fig. 17).

The simulation model has also given some indication as to the combined effect of successful weather modification and vegetation management practices. Under this alternative, comparisons were made between the natural water balance and the resulting balance from manipulating the calibrated model to simultaneously account for: (1) patchcutting the watershed so that 40 percent of the area was in openings five tree-heights in diameter; and (2) increasing the winter snow accumulation by 15 percent. The combined effect of snowpack increase and timber harvesting (table 6) was to increase the average annual water yield from 16 percent when the snowpack was increased under no-harvest conditions to 32 percent when coupled with the simulated timber harvesting practice. Although patchcutting accelerated snowmelt, the 15 percent increase in snowpack delayed the melt process somewhat, which resulted in an insignificant change in the duration

Table 6.--Simulated hydrologic changes resulting (1) from a 15 percent snowpack increase and (2) from combined snowpack increase and timber harvesting on Deadhorse Creek, Fraser Experimental Forest (Average of 1947-71 water years)

Component	15 percent snowpack increase			Combined snowpack increase and timber harvesting		
	Natural	Treated	Change	Natural	Treated	Change
	- - - - - - - - - - *Inches*	- - - - - - - - - -				
Precipitation	30.6	33.0	+2.4	30.6	33.0	+2.4
Evapotranspiration	16.8	17.0	+.2	16.8	14.8	-2.0
Recharge requirements:						
Beginning (Oct. 1)	3.5	3.5	0	3.5	2.4	-1.1
End (Sept. 30)	3.5	3.5	0	3.5	2.4	-1.1
Water yield	13.8	16.0	+2.2	13.8	18.2	+4.4

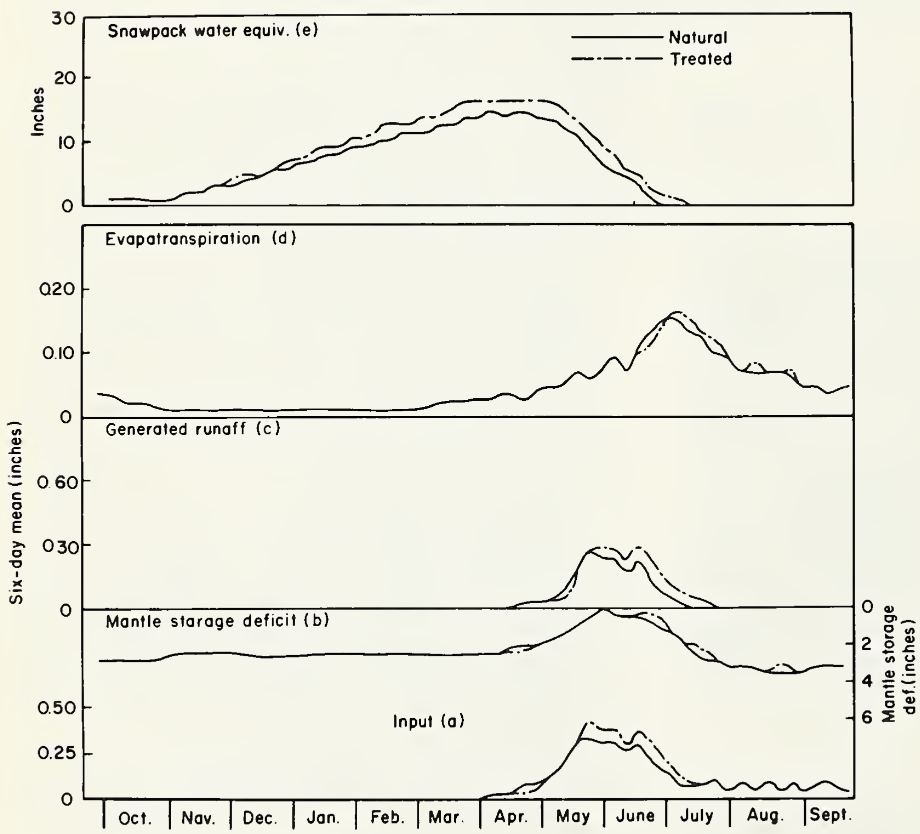


Figure 16.—Simulated average water balance for the 1947-71 water years, showing changes resulting from a 15 percent increase in winter snow accumulation on Deadhorse Creek, Fraser Experimental Forest.

of the snowmelt season. Evapotranspiration was increased from February until mid-June, but diminished thereafter with a net reduction of approximately 2 inches. Virtually all of the decreased recharge requirement of approximately 1 inch resulted from the effects of timber harvesting.

Our simulation analyses of the hydrologic effects of weather modification support recent results from field studies of tree growth and herbage production in the subalpine zone. Frank (1973) observed that a 10 percent increase in peak snowpack due to cloud seeding has "little, if any, immediate effect on the productivity and

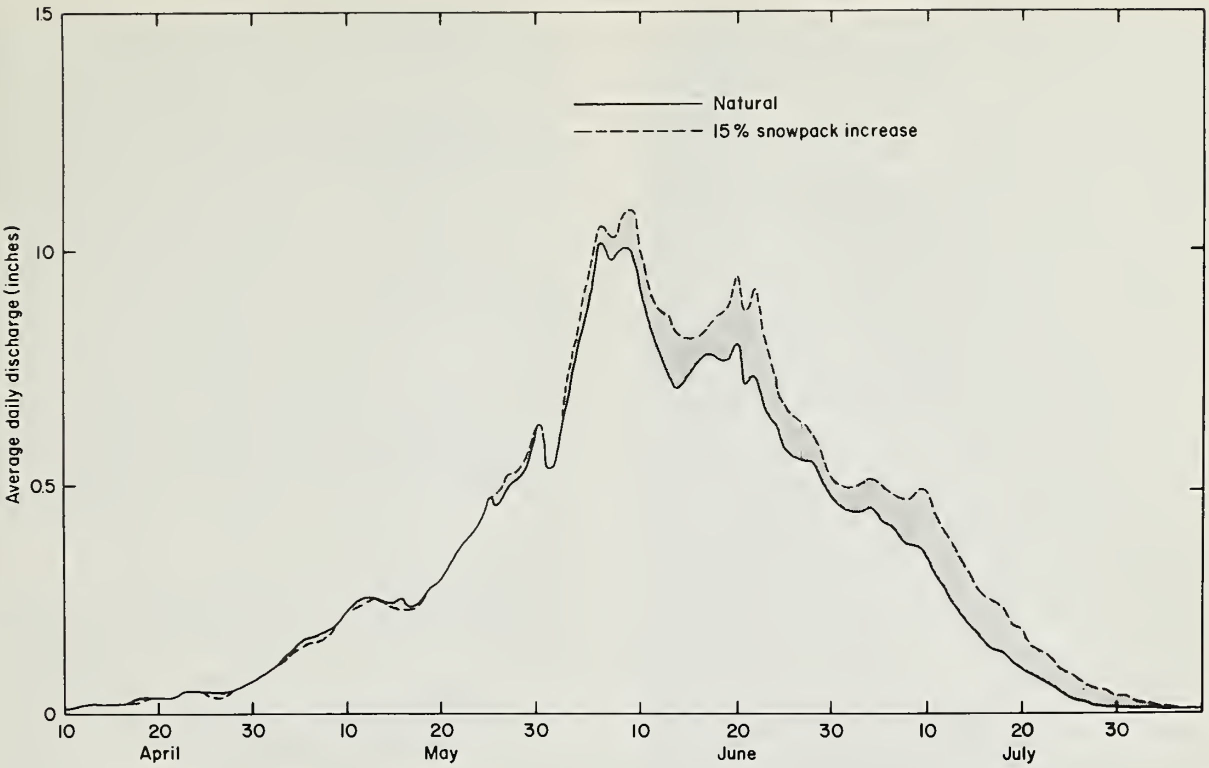


Figure 17.—Simulated hydrographs showing the average effect of a 15 percent snowpack increase on quantity and timing of streamflow for 1967-71 on Soda Creek near Steamboat Springs, Colorado.

use of mountain grasslands." Gary (1974) analyzed Engelmann spruce tree rings and snow accumulation in the Sangre de Cristo Mountains. He found that "increased snowfall will have little detrimental effect on the annual or long-term radial growth of the existing forest stands." Finally, studies of snow-cover depletion by Haeffner and Leaf (1973) have provided information on dates of final melt (last snow patches) on Bureau of Reclamation cloud-seeding project areas. Snow-cover data obtained during wet and dry years revealed that the time required to reach a given percentage of snow cover in late spring is more dependent on the magnitude of the snowpack during low runoff years than during high years. Thus, winter snow accumulation higher than normal does not delay disappearance of the last snow.

Long-term Simulation: Subalpine Land Use Model

The Subalpine Water Balance Model discussed above was designed to predict the short-term effects of timber harvesting on snowmelt and water yield. The model has recently been expanded to determine the long-term interactions between the water and timber resources with respect to partial cutting and regeneration practices in old-growth subalpine forest (Leaf and Brink 1975). This system (Subalpine Land Use Model) utilizes output from Subalpine Water Balance Model (see fig. 13).

The analytical framework of the Land Use Model is based on a "planning unit" which is defined by environmental characteristics including combinations of slope, aspect, elevation, and the species, form, and structure of the forest cover. The model is designed to simulate the hydrologic effects of timber harvesting in order to develop management strategies for planning intervals which can vary from a few years to the rotation age of subalpine forests (120 years and longer).

Because climatological observations are rarely available for the long periods of time simulated, the system has the capability to extend a sample data base by a randomized selection of water years until the desired planning interval is completed. Management strategies may subdivide a given planning unit into as

many as eight distinct areas or "response units," which may be managed independently at varying points in time during the planning interval. Provision is also made so that different cutting practices may be imposed on the response units, and finally, any number of cuttings may be made on a given response unit at specified years during the planning interval.

Figure 18 shows how the Subalpine Water Balance Model is used in executing alternative management strategies. Hydrologic integrity is maintained as management strategies are formulated, since all interactions between the various response units are accounted for in time and space. The interactive effects of a new decision on ones previously implemented are simulated, as are the effects of time, as demonstrated through reforestation. Moreover, the overall hydrologic effects resulting from each management decision on the planning unit are projected to the end of the planning interval as though it were the final decision in the strategy. Thus, the singular effects of each decision can be evaluated.

The Land Use Model utilizes output from the Subalpine Water Balance Model, which simulates the water balance on a daily basis. On those areas where forest cover has been removed, the parameters which define soil water availability, forest cover density, reflectivity, interception, and snow distribution are adjusted on an annual basis by means of time-trend relationships. The procedure used in formulating each time-trend relationship was to: (1) establish plateaus, and maximum and minimum values for each hydrologic variable; (2) establish critical times at which a transition begins to occur; and (3) assume a functional relationship which determines all intermediate values.

Due to our lack of understanding of long-term hydrologic phenomena, the time-trend equations are not 'right' in any intrinsic or mathematical way. They should be considered only as relationships which represent our best estimates of how the most significant processes vary over a long period of time. We believe the time-trend relationships are plausible; however, additional research is needed before more accurate equations can be developed.

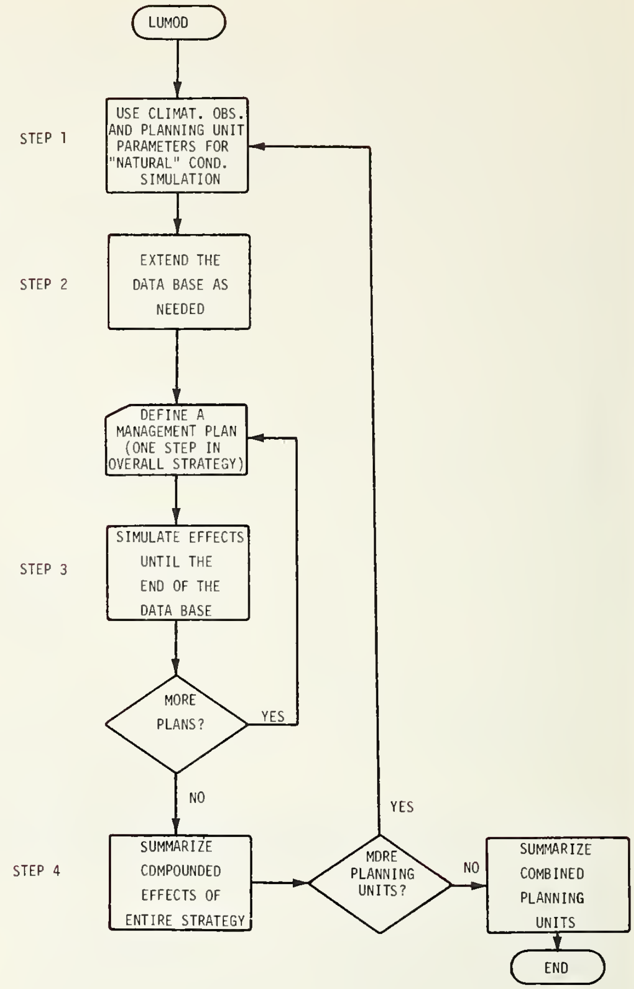


Figure 18.—Flow chart showing how Subalpine Water Balance core model is used to execute alternative management strategies.

Application of simulation model.—The Subalpine Land Use Model has been used to simulate the long-term effects of a hypothetical forest and watershed management strategy on Wolf Creek, in southwestern Colorado. The planning unit selected for this example has a northwesterly aspect and an average elevation of 10,000 ft m.s.l. The average slope is 15 percent, and forest cover is spruce-fir.

In addition to improving water yield, the management strategy selected for this example essentially has followed recommendations by Alexander (1973), which are keyed to stand descriptions, insect and disease problems, and windfall risk situations. Under this strategy, all of the old-growth timber would be harvested in a series of patchcuts spread over a planning interval of 90 years. At intervals of 30 years, approximately one-third of the area would be harvested in small openings—five to eight times tree height—distributed over the watershed. Forest openings would be constructed in a balanced and unified pattern so as to minimize visual impact on the natural landscape.

At the end of the planning interval, all of the openings would have regenerated and the watershed would contain groups of trees in sev-

eral age classes from reproduction to larger trees on the originally cutover areas. The management strategy would maintain a forest cover throughout the planning interval, and would insure regeneration of the stand from small trees on the cutover area, and from a seed source provided by mature trees surrounding the forest openings.

Projected average annual water-yield increases in 10-year increments under this management strategy for the 90-year planning interval are tabulated in table 7. The increases above the line through the data represent the overall response at any given time resulting from preceding management decisions. The data below the line reflect the singular effect of the initial patchcut on one-third of the planning unit, assuming that it was the final decision in the strategy.

Table 7.--Projected changes in water yield resulting from timber harvesting, Wolf Creek planning unit, San Juan National Forest, Colorado

Interval (Years)	Water yield increase after patchcut treatment-- I	II	III
	- - - - *Inches/year* - - - -		
0 - 10	+2.1		
11 - 20	+1.4		
21 - 30	+1.8		
31 - 40	+.72	+2.9	
41 - 50	+.34	+2.9	
51 - 60	+.11	+1.8	
61 - 70	+.19		+3.4
71 - 80	-.06		+2.1
81 - 90	+.23		+2.7

Water yields would be improved throughout the planning interval. Projected runoff increases during each treatment interval are as follows:

Treatment	Runoff increase (Percent)
I	6.8
II	9.4
III	10.1

The effect of the initial patchcut (Treatment I) would apparently persist for at least 50, and perhaps 60 or more years. Thereafter, the effect on water yield, for all practical purposes, would be negligible.

Simulation models as planning tools.—Research has shown that any management decision which leads to timber harvesting will have an impact on the water resource. Furthermore, any decision in the subalpine environment is, for all practical purposes, "for keeps." Hence, the cut-and-try approach in resource management is simply no longer acceptable. We need rational conceptual models to evaluate watershed management strategies. The comprehensive simulation models described in this report represent our first step in providing the practicing hydrologist and land manager with planning tools that utilize our best technical knowledge of fundamental hydrologic processes. One additional favorable aspect of the models is that they are no more complex than required to provide necessary information. Moreover, application of the models is not unduly restricted by data requirements. We believe that, for the most part, basic hydrologic data currently available in the Rocky Mountain region are adequate for operational use. The hydrologic impacts of the watershed management practices discussed above are but a few examples of numerous alternatives that have been simulated. The models have been tested and calibrated on several representative drainage basins in Colorado (Fraser River, Arapaho National Forest; Wolf Creek, San Juan National Forest; Trinchera Creek, Sangre de Cristo Mountains) and Wyoming (South Tongue River, Bighorn National Forest; East Fork of the Encampment River, Medicine Bow National Forest).

Erosion and Water Quality

Sediment Yield

Forest management requires roads. Unfortunately, some roads have been located too close to streams, built on too steep grades, and inadequately drained. A few obviously bad examples of road construction in the subalpine zone have caused many influential laymen to conclude that "roads are detrimental to soil stability, streamflow quality, and fisheries; that roads have adverse effects on big-game populations; and, finally, that roads are ugly" (Wyoming Forest Study Team 1971). However, several studies of the effects of careful logging and road construction on erosion and water quality indicate that this need not be the case. Research has shown that watershed erosion and damage to water quality from road construction and timber harvesting can be significantly reduced

through proper planning, construction, and followup maintenance (Packer and Laycock 1969, Megahan 1972).

For example, Leaf (1970) showed that, on Fool Creek in central Colorado, road construction resulted in minimum erosion damage with apparently no reduction in water quality. The 3.3 miles of main access road were carefully located to avoid the stream channel and to minimize erosion. Timber was made accessible by an additional 8.8 miles of spur roads laid out along contours. Spur roads were provided with surface drainage and culverts at stream crossings. In 1957, after logging was completed, spurs were seeded to grass, and culverts were removed on alternate roads to reduce traffic. Routine followup maintenance is still done on the main haul road.

Sediment yield during road construction and following extensive logging on the Fool Creek watershed averaged about 200 pounds per acre, compared with an average 88 pounds per acre for this period of record (table 8). Yield decreased rapidly after 1958, despite the persistent increase in runoff caused by the harvest. Since 1958, annual sediment yield from Fool Creek has averaged 43 pounds per acre, compared with yields of from 11 to 21 pounds per acre from the undisturbed watersheds. Suspended sediment was less than 5 parts per million (p/m) during high flow periods in 1964 and 1965.

Again, these results indicated that "sediment yield need not be excessive after harvest cutting on small forested watersheds in central Colorado, provided that reasonable erosion control measures are applied during logging and road construction. Sediment yields are relatively high in the years during and immediately following these activities, but decrease rapidly in subsequent years toward preharvest levels" (Leaf 1970).

Table 8.--Annual sediment yields (pounds per acre) on Fool Creek watershed since harvest cutting and road construction (Leaf 1970)

Year	Sediment yields on--		
	Fool Creek (714 acres)	Deadhorse Creek (667 acres)	Lexen Creek (306 acres)
	- - - *Pounds/acre* - - -		
1952	[1]204		
1953	102		
1954	[2]Negligible		
1955	[2]Negligible	20	
1956	[2]166	84	32
1957	318	111	56
1958	194	10	66
1959	39	24	12
1960	63	24	11
1961	28	5	2
1962	74	62	28
1963	Negligible	4	1
1964	Negligible	7	9
1965	113	35	18
1966	25	4	7
Average	88	32	22

[1]Road construction.
[2]Timber harvest.

Sediment yield simulation model.—One of the more significant results from sediment yield studies in mountain watersheds is that most of the erosion impact is concentrated within a few years after disturbance (Leaf 1970, Megahan 1974). This time factor should not be overlooked in land use planning from both the standpoint of protection and the long-term effects on hydrologic parameters such as water quality.

Equations that require erodibility indices based on rainfall intensity may be grossly in error when applied to much of the subalpine zone, where much of the sediment yield can result from melting snow. Accordingly, a simulation model based on equations developed by Megahan (1974) was developed to predict the impacts of secondary logging road construction on erosion and sediment yields (Leaf 1974).

The primary equation in the model is a negative exponential function with a linear component containing three parameters. This equation describes the time trends in erosion and sediment yield discussed above. Numerical values of the parameters were determined, using the data summarized in table 8.

The time-trend equation is used in combination with another expression which computes the area disturbed by road construction. This equation is formulated in terms of the following watershed and engineering design parameters: (1) width of roadbed; (2) average watershed side slope; (3) number of miles of road system; and (4) angle of cut and fill. It assumes balanced cut and fill (that is, that the centerline bisects the road width). Although this is not usually the case, since the cross section can vary from total cut to total fill in actual practice, it is assumed that a sufficiently accurate index of the total area disturbed can be obtained by estimating an "effective" width and average cut and fill slope for the proposed road system. Such estimates require considerable judgment and knowledge of the topography.

Three additional assumptions were made to develop the model for predicting erosion and sediment yields:

- The model provides a better index of erosion than equations based on rainfall-derived erodibility indices. Such indices do not predict time trends, and furthermore, do not account for the effects of snowmelt.
- Onsite erosion is proportional to the area disturbed.
- The delivery ratio is constant for a given watershed size, regardless of the amount of area disturbed.

These assumptions involve complex interactions between the hydrology, geology, and soils, which need to be verified by additional study.

Because the model is formulated in terms of engineering design variables, its use should provide an indication of the probable erosion impacts of alternative road systems. The coefficients were developed from a limited amount of data obtained from a carefully constructed road system and a high standard of followup maintenance; hence, they may not be generally applicable throughout the Rocky Mountain region. They should be considered as tentative estimates until more data become available. Any application of the model should presume similar standards of construction and maintenance. The model is a subroutine of the Subalpine Land Use Model developed by Leaf and Brink (1975).

Sediment yields from subalpine ranges.—Frank[7] computed annual sediment yields from the Black Mesa watersheds in Colorado by integrating suspended sediment discharge during the runoff period. Suspended-sediment yields averaged 53 to 91 pounds per acre of herbaceous type on three watersheds. Suspected sources of sediment included the stream channels, gopher activity, and bare soil areas. All sources apparently contributed to the total load. Because these areas occupied only a small proportion of each watershed, Frank was unable to define the significance of the bare soil areas subjected to grazing by cattle "when the small sediment yield could be accounted for by a few specific areas where soil is readily available and probably removed by overland flow."

Chemical and Bacterial Water Quality

With the exception of those areas where geothermal activity and geologic conditions have mineralized the water, natural flows from the subalpine zone are as "pure as the driven snow" in comparison to low-lying areas. In general, concentrations of all the chemical components are low. The pH values are near neutral, and water temperatures are cold (0° to 7°C). Kunkle and Meiman (1967) determined the chemical composition of water in the Little South Fork of the Cache la Poudre River in Colorado; Stottlemyer (1968) and Frank[8] made similar analyses on several small watersheds at the Fraser Experimental Forest (table 9).

Effects of timber harvesting.—Research in temperate climates has shown that timber harvesting usually causes increased loss of plant

[7]Frank, Ernest C. Hydrology of Black Mesa watersheds. (Manuscript in preparation at Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo.)

[8]Personal communication with Ernest C. Frank, Hydrologist, Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo.

Table 9.--Average chemical composition (in parts per million) of selected high-elevation Colorado streams

Watershed	Ca	Mg	Na	K	CO_2	HCO_3	Cℓ	PO_4	SO_4	NO_3	SiO_2
Cache la Poudre:											
Little South Fork											
1965 (Kunkle and Meiman 1967)	2.7	6.5	1.0	0.5	1.6	18.9	5.0		14.6	0.8	
Fraser Experimental Forest:											
Deadhorse and Lexen Creeks											
1965 (Stottlemyer 1968)	6.9	3.1	1.5	.6							
1971 (Frank,personal comm.)	14.5	6.0	4.5	1.0			3.0		10.0	1.0	8.0
Fool Creek											
1965 (Stottlemyer 1968)	2.1	1.1	2.0	.5							
East St. Louis Creek											
1965 (Stottlemyer 1968)	1.8	.8	1.4	.4							

nutrients. Pierce et al. (1972) reported that clearcutting a watershed in New Hampshire increased nitrate, calcium, magnesium, potassium, and sodium losses severalfold. However, little is presently known about water quality changes resulting from timber harvesting in the relatively dry, cool subalpine climate. A recent comparison of the quantity and composition of streamflow from Fool Creek and East St. Louis Creek watersheds in central Colorado has provided at least some indication of effects of timber harvesting on chemical water quality. Stottlemyer and Ralston (1968) computed the following average annual losses of cations from the two watersheds:

	Cation concentration (p/m)	Cation outflow (lb/acre)
E. St. Louis Creek	4.5	22.9
Fool Creek	6.3	28.1
Difference	+1.8	+5.2

These data are based on samples taken twice each week during a 10-week period in the summer of 1965. Unit cation outflow from Fool Creek was 5.2 pounds per acre higher than from East St. Louis. Frank[8] suggests that this small difference may not accurately reflect water quality changes 10 years after Fool Creek was logged, however, since 1965 was a high snow year. He points out that normal or deficient annual runoff might show higher differences in concentration and outflow, depending on the relative change in timing and volume of discharge.

Bacterial water quality.—Kunkle and Meiman (1967) studied bacterial water quality on the Little South Fork of the Cache la Poudre River, which they said may be considered to be representative of the subalpine zone. Many subalpine watersheds support domestic livestock and big-game through the summer months and are heavily used for recreation.

Bacterial counts were made in 1964 and 1965. In 1964, Kunkle and Meiman found an extremely wide range of total bacterial counts, which varied from several million colonies per ml down to less than 10,000 colonies per 100 ml. They observed a "strong, positive bacteria to flow relationship." High bacterial concentrations associated with grazing and recreation appeared to depend on the "flushing effect" of flooding during peak snowmelt and summer storm runoff periods. Also, they observed that the "broad seasonal trend for the coliform, fecal coliform (FC), and fecal streptococcus (FS) bacterial groups was similar: (1) low winter counts prevailed while the water was 0°C; (2) high concentrations appeared during the peak flows of June; (3) a 'post-flush' lull in counts took place as the hydrograph declined in midsummer; (4) high concentrations were found again in the late summer period of warmer temperature and low flows; and (5) counts declined with the arrival of autumn." Kunkle and Meiman also observed low bacterial concentrations in winter. Bacterial concentrations varied widely at all sampling sites. Coliforms fluctuated from zero to about 300 colonies per ml, depending on the site and season. FC and FS fluctuated less, from zero to 75 colonies per 100 ml. At the high-elevation sites, FC and FS counts were near zero, and coliform counts were less than 40.

It should be noted that very little, if any, information is available on the effects of timber harvesting on the bio-active components of water quality. In all probability, any changes in bacterial concentrations resulting from harvest cutting are considerably less than those brought about by other forms of increased human activity such as housing, mining, and recreation developments.

Conclusions

At the outset, this report addressed itself to the question: "To what extent are we able to recommend forest management practices to improve water yield and still maintain acceptable quality, quantity, and timing?" The following paragraphs highlight technical aspects of the status of our knowledge in watershed management, and summarize principles that are important for efficient multiple use management of the subalpine zone.

- Patchcutting subalpine forests results in significant redistribution of the winter snowpack. Snow accumulation patterns are optimum when openings are: (1) less than eight tree heights in diameter; (2) protected from wind; and (3) interspersed so that they are five to eight tree heights apart. Because more snow is deposited in the openings, and less snow accumulates in the uncut forest, total snow storage on headwater basins is not significantly increased.
- On all aspects, snowmelt in clearcut openings is more rapid than in the uncut forest. This accelerated melt causes streamflow to be higher on the rising limb of the hydrograph than before harvest cutting. Where

there is considerable natural regulation in the form of deep porous soils, recession flows are not changed appreciably and annual flood peaks are not significantly increased, **provided that** the forest cover on no more than 50 percent of the watershed is removed in a system of small openings.

- In central Colorado, when 40 percent of the 1- to 3-mi^2 subalpine watershed is occupied by small openings, and 60 percent is left uncut, annual water yields are increased at least 2 inches. Interception loss is decreased, but increased evaporation from snow surfaces in the openings almost compensates for the decreased interception loss so that total input is increased less than half an inch. Average recharge requirements on the basin are decreased by about 1 inch and evapotranspiration during the growing season is decreased by more than 1.5 inches. Simulation analyses indicate that, under this alternative, water-yield increases on low-elevation south aspects in lodgepole pine forest are as large as corresponding increases from high-elevation north aspects in spruce-fir. Hence, there is no reason to favor areas having the highest natural water yield if the objective is to maximize water yields from medium to dense old-growth forest.
- Due to the considerable length of time it takes for coniferous subalpine forests to grow to maturity, increased water yields from patchcutting can go essentially undiminished for perhaps 20 years and longer. It is conceivable that 30 additional years will be required before runoff increases from the initial timber harvest are completely erased.
- The **pattern** in which trees are harvested determines whether or not runoff will be increased. Streamflow increases are greatest when subalpine forests are harvested in a system of small forest openings. Simulation analyses indicate that when the forest is harvested in large clearcut blocks, or by selectively cutting individual trees, overall water-yield increases are far less than those attained if the same amount of timber volume is removed by patchcutting. When the canopy density is reduced 50 percent by selective cutting in spruce-fir forests on northerly aspects, water yields may actually be decreased. In lodgepole pine forest, water yields can be increased somewhat by selection cutting, provided that cuts are made on southerly aspects and at low elevations where the snowmelt season is short and begins relatively early in the spring.
- The timber harvesting measures recommended for maximum water yields are silviculturally sound and compatible with the guidelines recently developed from research in old-growth lodgepole pine and spruce-fir. Patchcutting would enhance wildlife habitat, and preserve the natural landscape by maintaining a high forest cover in areas where recreation and esthetics are important.
- Timber harvest measures recommended for maximum water yields should not be detrimental to water quality or excessively increase erosion, **provided that** timber harvesting is executed with proper planning, engineering, construction, and followup maintenance. Sediment yields can be relatively high immediately following road construction, but should decrease rapidly toward preharvest levels. Several studies in the Rocky Mountain and Intermountain regions document this time-trend pattern, even though soils and geology vary over a wide range of conditions. These conclusions apply only to **surface erosion,** and not to **mass erosion,** which can occur after disturbance of very steep and naturally unstable slopes.
- Results from the Subalpine Water Balance Model indicated that, in central Colorado, a 15-percent increase in snow accumulation through successful weather modification will increase water yields 16 percent in the average year. Weather modification apparently will not extend the snowmelt season more than 3 to 5 days, and apparently does not significantly affect evapotranspiration. Because water-yield benefits result from the last snowmelt at a given location, the bulk of the increased runoff is released during and just after peak streamflow. This would have a tendency to broaden the snowmelt hydrograph and possibly increase peak flows in small headwater streams. Successful augmentation of natural snowfall in combination with vegetation management practices will significantly increase water yields. In central Colorado, if 40 percent of a watershed were harvested in small patches five tree heights in diameter, water-yield increases could be doubled if the natural snowpack were also increased by 15 percent.
- Dynamic simulation models have been developed from the best information we presently have about subalpine hydrologic systems. The models have been calibrated, using data from representative watersheds in old-growth lodgepole pine and spruce-fir forests throughout the Rocky Mountain region. They have been designed to predict the short- and long-term hydrologic impacts of a broad array of watershed management practices. Hydrologic changes can be determined for intervals of time from a few years

to the rotation age of subalpine forests (120 years and longer). These predictions are based on time-trend functions which compute changes in evapotranspiration, soil water availability, forest cover density, reflectivity, interception, and snow redistribution after timber harvesting. These models produce the type of information hydrologists and land use planners need to make difficult management decisions. The ability of the models described here and other similar models to integrate complex forest and water systems makes them unique and powerful tools for evaluating the hydrologic effects of a broad array of land management alternatives.

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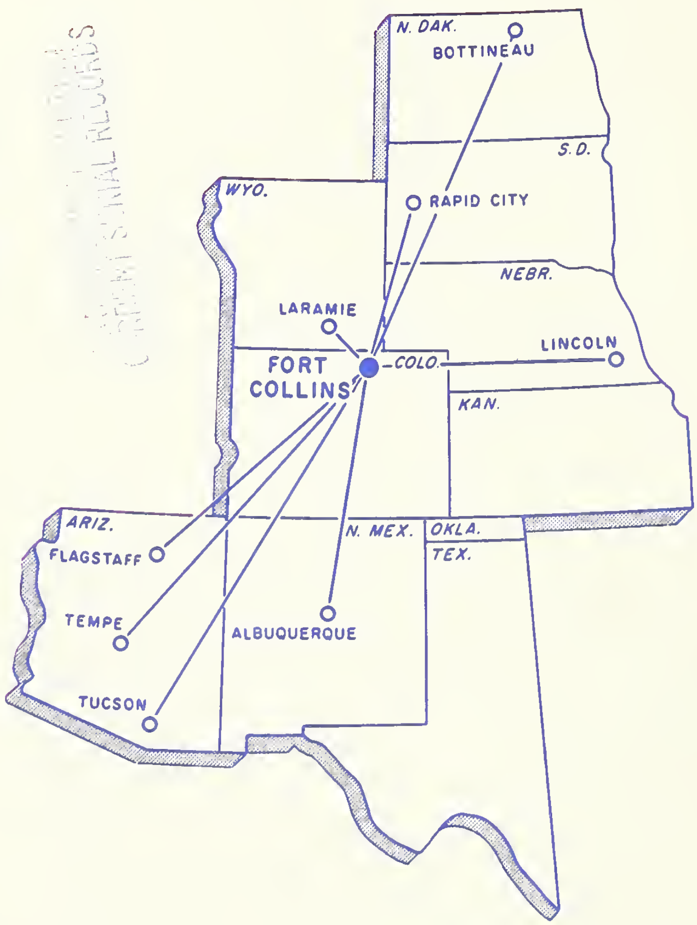
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